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Implementing Digital Earth: A Research Agenda

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ABSTRACT Models of the Earth include maps, and also mathematical models of processes that modify the Earth s surface. The concept of Digital Earth originated with the published text of a speech made by U.S. Vice President Gore in 1998. It implies smooth transition and integration across a wide range of scales from global to local, and the use of digital technology. Research issues arise in the areas of data structures, indexing schemes, data integration, semantic integration, cartographic technique and visualization, and institutional arrangements.

KEY WORDS Digital Earth, GIS, Research Agenda, Scale

1. Introduction

The earliest models of the Earth were created millennia ago, when people first began to record knowledge of their immediate surroundings by arranging sticks, or by making marks on the ground or on cave walls. The technologies of surveying and cartography flourished under many cultures and civilizations, and by the 16th Century had developed into a complex and accurate set of practices concerned with modeling the surface of the Earth by projecting it onto a flat sheet of paper. The use of spherical globes allowed models to avoid the distortions associated with projection, but at the expense of high marginal costs of production and distribution. Today, models of the Earth s surface are part of our everyday lives, as we learn, navigate, read newspapers, or watch television.

Maps and globes are models only of the static aspects of the Earth s surface, since once constructed they are difficult to modify. Models of changing aspects of the Earth, and of the processes which modify it, are much more recent. Models of climate rely on the basic physics of the atmosphere and its representation in mathematical models dating from the 18th and 19th Centuries. The models of von Thunen, Weber, and Christaller, which deal with the distribution of economic activities and their response to changing patterns of behavior, date only from the early 20th Century. Models of urban growth are even more recent, as are models of geomorphological processes.

Besides this basic distinction between static and dynamic, these various models embody two distinct ways of dealing with geographic phenomena. Maps are analog representations of the surface itself, scaling phenomena such that distance on the map is in roughly constant proportion to distance on the Earth. On the other hand, models of processes are general, abstracting from the Earth s surface to general statements about how various systems operate. In order to predict specific forms on the Earth s surface, it is necessary to combine knowledge of process in the form of a general model with knowledge of specific local conditions, or *boundary conditions*, to use the term that is common in physics and other areas of modeling. Bernhardus Varenius called these two forms of geographic knowledge *general geography* and *special geography* respectively. The term *idiographic* is often used to refer to special knowledge of the properties of places, and *nomothetic* to refer to general knowledge of processes.

Today s geographic information systems nicely combine the special and the general, or the idiographic and the nomothetic. A model of urban growth implemented in a GIS, for example, requires the modeling of general knowledge in its algorithms, and the modeling of special knowledge in its database layers. The naming of the Varenius project of the U.S. National Center for Geographic Information and Analysis (Goodchild *et al.*, 1999) reflects the contribution of Bernhardus Varenius, and the echo of his distinction in modern GIS-based science and decision-making.

Digital Earth is thus the latest in a long series of efforts to model both the specific and the general aspects of the Earth s surface and its near-surface. It differs from previous efforts in two important ways, however:

- It is global, bringing knowledge of all parts of the Earth into a single computational environment;
- It is digital, representing knowledge exclusively in digital form.

Both of these innovations bring advantages, but at the same time they present challenges that are both institutional and technical in nature.

This paper is organized as follows. The next section reviews the concept of Digital Earth, its origins, and its meanings. This is followed by sections that discuss the implications of the two points above—its global nature, and its digital nature—and sketch elements of a development agenda. The paper ends with a concluding section summarizing issues for research.

2. The Concept of Digital Earth

It is widely accepted that the term *Digital Earth* (DE) originates with the published version of a speech of the U.S. Vice President, Al Gore. In it, he describes an immersive environment that would allow its users to explore and learn about the Earth and its human and physical environments (the full text is at *www2.nas.edu/besr/238a.html*; a summary was delivered in Los Angeles in January 1998):

"Imagine, for example, a young child going to a Digital Earth exhibit at a local museum. After donning a head-mounted display, she sees Earth as it appears from space. Using a data glove, she zooms in, using higher and higher levels of resolution, to see continents, then regions, countries, cities, and finally individual houses, trees, and other natural and man-made objects. Having found an area of the planet she is interested in exploring, she takes the equivalent of a 'magic carpet ride' through a 3-D visualization of the terrain. Of course, terrain is only one of the numerous kinds of data with which she can interact. Using the system's voice recognition capabilities, she is able to request information on land cover, distribution of plant and animal species, real-time weather, roads, political boundaries, and population. She can also visualize the environmental information that she and other students all over the world have collected as part of the GLOBE project. This information can be seamlessly fused with the digital map or terrain data. She can get more information on many of the objects she sees by using her data glove to click on a hyperlink. To prepare for her family's vacation to Yellowstone National Park, for example, she plans the perfect hike to the geysers, bison, and bighorn sheep that she has just read about. In fact, she can follow the trail visually from start to finish before she ever leaves the museum in her hometown.

She is not limited to moving through space, but can also travel through time. After taking a virtual field-trip to Paris to visit the Louvre, she moves backward in time to learn about French history, perusing digitized maps overlaid on the surface of the Digital Earth, newsreel footage, oral history, newspapers and other primary sources. She sends some of this information to her personal e-mail address to study later. The time-line, which stretches off in the distance, can be set for days, years, centuries, or even geological epochs, for those occasions when she wants to learn more about dinosaurs."

Several principles and challenging ideas underlie this piece of technological fantasy. First, the immersive environment provides a very rich form of communication between the information store and the learner, unimpeded by the constraints of a single medium, and not limited to the visual channel or to the narrow concept of map defined earlier. Second, the vision mixes types of data that are readily communicated by rendering into something resembling their true appearance, such as topography and land cover, with other types that will have to be communicated symbolically. This second type includes information on population, health, or environmental quality. Cartographers are familiar with the problems of mixing these two types through their experience with symbolic enhancement of orthographic images. Other information mentioned in the speech is geographic only in the sense of having a footprint; the contents of newspapers and oral histories will have to be represented iconically, and their contents communicated in some appropriate way, since they are not geospatial and therefore cannot be mapped onto the Earth s surface.

More fundamentally, perhaps, DE embodies a novel metaphor for the organization of digital information and construction of user interfaces. The current generation of computer operating systems, such as Windows 98, makes use of the metaphor of the desktop, with its clipboards, filing cabinets, and briefcases, because this is the environment most familiar to office workers. This tradition goes back to work at the Xerox PARC laboratories in the 1960s, but came to dominate Microsoft operating systems only in the late 1980s with Windows. Yet the office is not a natural environment for thinking and learning about the surface of the Earth, and office is not the first thing that comes to mind when we think of Columbus, or von Humboldt. Since all such information relates to some geographic location, it would be far more effective to use the Earth s surface itself as the organizing metaphor. For example, rather than look in a filing cabinet under Z, someone interested in Zimbabwe would find it much easier conceptually to reposition a digital globe to the right part of Africa (or to look up Zimbabwe in a digital rendering of the back-of-the-atlas gazetteer, and see the globe repositioned automatically). DE replaces the office with the Earth as the dominant user interface metaphor. In that sense it offers a significant contribution to the growing interest in digital libraries that support search for information by geographic location, or geolibraries (NRC, 1999).

Finally, DE is not static. In an immersive digital environment, and given sufficient general knowledge in the form of models of processes, it is possible to imagine the user of DE being able to simulate future environments, by executing models of urban growth, or species extinction, or tectonic uplift, and observing their consequences for any part of the Earth. It is also possible to imagine modeling past environments, by running simulations backwards in time. In this regard, DE is seen as having immense power for education. A static DE would be a good basis for learning the facts of the Earth s special geography. But a dynamic DE would allow students to explore the processes of general geography, and their implications, in compellingly realistic form and using boundary conditions representing environments that are familiar to them. For example, a student would be able to learn about tectonic processes by modeling the appearance of California 1, 10, or 100 million years from now.

The speech has spawned a substantial level of interest in DE, as a search of the WWW will reveal. DE projects are under way to model tectonic and other geophysical processes, to explore Earth imagery, to deliver the services of a map and imagery library, and to teach about the Earth and its human and physical phenomena (www.alexandria.ucsb.edu/adept). An interagency working group has been meeting for the past two years under the auspices of the U.S. National Aeronautic and Space Administration.

3. Global to Local

The first of the two unique aspects of DE identified earlier is its global focus. Humans are most familiar with their immediate surroundings, and make frequent use of maps in navigating and finding unfamiliar places. They also use globes and atlases that present global perspectives, but many discontinuities occur between the local and the global. For example, the projections used for global data are different from those used locally. We are used to seeing the United States presented in conic projection, which curves the 49th Parallel forming the western part of the border with Canada. But the whole Earth is often presented in Mercator projection, which looks decidely unfamiliar as the basis for a map of the United States alone. Today, the whole Earth is often presented in orthographic projection, because we are increasingly familiar with how the Earth looks from space.

Linking global and local perspectives is also complicated by our traditional arrangements for production of geospatial data. Nations support national mapping agencies for reasons having to do with both military and civilian functions, and some nations support the production of global data. But production is typically organized by theme, with different agencies being responsible for maps of soils, topography, land use, or population, and in some cases different agencies are responsible for maps of the same theme at different scales. Only the atlas attempts to integrate maps of many themes, and integration of detailed local data remains an important technical challenge, as does the integration of data on the same theme across wide ranges of scale. When two maps of widely different themes are merged, it is common to find a failure to fit, because of the positional inaccuracies in both maps, even though they are nominally at the same scale.

DE challenges many of these traditional impediments. It implies an ability to move smoothly from the global scale to the local. A display of the whole Earth on a computer screen implies a resolution of about 10km, whereas a display of a local neighborhood might require a resolution of 1m. Thus to achieve the zooming requirement of DE it would be necessary to move smoothly and quickly over a range of scales of perhaps 104. Moreover, to zoom over this range of scales for a single data theme implies the integration of a range of different data sources, and techniques to join them smoothly. A 10km image of the Earth might be created by compositing AVHRR (Advanced Verhy High Resolution Radiometer) images and coarsening their resolution; below 1km the source would have to change, perhaps to TM (Thematic Mapper) imagery, which has different spectral and temporal characteristics. Below 30m the source would have to change again, to one of the new high-resolution TM emulators. Some of these technical issues have been overcome in limited environments, including videos that appear to achieve continuous and smooth zoom, but DE imposes new standards of flexibility and generality.

Smooth integration also implies that differences in projection, datum, and data structure can be overcome. The rasters of Earth imagery are inherently flat, and discontinuities must exist at the boundaries of image tiles. A single DE coverage of the Earth would require seamless integration, and the use of a single tesseral scheme. Recent research (e.g., Goodchild and Yang, 1992) has explored consistent tesselations of the globe, and many possible schemes have been defined. It is impossible, however, to define a perfect scheme that is regular and uniform, and each scheme has its advantages and disadvantages. DE technology will need to support one or more of these schemes, and it would be helpful if standards could be defined and adopted.

Global schemes such as those just discussed are needed both for the representation of geographic data, and for the indexing of those data for fast access and retrieval. In some instances, the same scheme serves both purposes in spatial databases, as in the quadtree scheme, where the same tree structure is used both to describe spatial variation, and to index information. In other instances two different schemes are used, as when a quadtree is used to index vector data.

Smooth transition between global and local data also implies the integration of semantics, or the definitions of themes and attributes at different scales. For example, the concept urban exists only at certain scales; below them, homogeneous urban areas break up into heterogeneous collections of buildings, pavement, grass, or trees. Because past practice has separated the production of geographic data at different scales, these problems of semantic integration across scales have been largely ignored, but DE will force us to address them, along with the inevitable effects of positional inaccuracies.

Finally, models of process have their own ontologies, that may or may not coincide with the ontologies of static geographic information. For example, many models of ocean processes use finite difference representations, which we would recognize in the GIS community as rasters. But models of tidal estuaries often use finite element representations, with irregular primitive elements that are triangles or quadrilaterals, and of these only TINs are commonly supported in GIS, and then only partially. Hydrologic models use many different representations, depending on whether the approach is spatially aggregated or disaggregated, and whether models include surface or subsurface hydrography, or both. Some of these representations can only exist in a flat, projected world, raising issues of how they are to be implemented in spherical schemes such as those discussed above. Global climate models avoid spatial representations altogether, and discretize instead in the spectral domain. Inevitably, the need to integrate data and models in a consistent DE structure will force compromises between different representations, and it will be difficult to find solutions that are satisfactory to all stakeholders. To date, only a very few efforts have been made to develop modeling environments for geographic phenomena that are universally applicable across many application domains (an example is PCRaster, developed at the University of Utrecht by Peter Burrough and his group).

4. Digital Models

By using digital technology, DE takes advantage of the enormous progress that has been made in the past several decades in hardware, software, databases, and networking. The fact that DE is being discussed at all, and that we are willing to share its vision, speaks to the expectation that the technologies needed to implement it are either here today, or will be here shortly.

A 10km resolution coverage of the Earth requires on the order of 107 elements, and occupies 10Mb at 1 byte per element. A 1m resolution coverage requires on the order of 1015 elements, or a petabyte at 1 byte per element, a volume which is considerably larger than the upper limit of today s affordable storage devices. Of course these numbers can be reduced somewhat by compression, depending on the nature of the coverage. But DE will clearly stretch the storage capacities of computing systems.

More problematic at this time is bandwidth. If we assume that the typical computer display has 106 picture elements, a full screen may display as much as 1Mb of data. Full video refresh rates of 25 frames per second or more will require bandwidths of order 100 megabits per second or more, which will stretch the capacities of current local area networks, and lies far beyond the capabilities of most Internet connections. What DE services, if any, will be deliverable to the average household now or in the future is an important question.

DE is presented in the Gore speech as an immersive environment, entered by donning a headmounted display. DE services might also be delivered in caves, or using 3D wallboards like the

Immersadesk. There will be instances where a user interacts alone with DE, and other instances where collaborative interaction by groups is appropriate, for example in classrooms where the display is managed by the instructor. Exactly which environments are appropriate for what purposes is an interesting research question.

The use of digital technology raises a host of questions about interaction modalities. Recently, there has been considerable interest in the GIS research community in handling vague information, on the grounds that humans occupy and communicate in an inherently vague world, and should therefore be able to use various forms of digital assistance, for example in reasoning with vague information. Underlying this discussion is the assertion that the digital geographic world has been inherently hostile to vagueness. Thus DE might follow past GIS practice by forcing all information and interaction to be precise, or it might be designed to accommodate various forms of vagueness. It might also be designed to implement some of the ideas being discussed under the rubric of public participation GIS, by handling multiple representations that capture the views of different participants in collaborative decision-making. Consideration of all of these issues is important as we discuss and evolve the concept of DE.

5. Concluding Comments

DE has been presented elsewhere as having the characteristics of a moonshot, or a vision that can unite research and development in pursuit of a single goal. Putting a man on the moon in the 1960s was such a goal, and it spawned a massive effort to develop new technologies and procedures, and new institutions. The effort produced short-term benefits in employment, and much greater long-term benefits in applications of its technologies, and stimulation of industrial activity. The goal of DE—the creation of an integrated digital model of the Earth that can be accessed by a broad user base, and used to learn and make decisions from local to global scales—has many of the same characteristics. Of course it is unlikely that its scale will compare to that of the moon program, and it lacks many of that program s compelling elements. But the moon program was characteristic of its time, when massive government-sponsored programs were considered feasible and attractive. Today, the aims of DE are more likely to be achieved through loosely coupled efforts driven by a common vision and purpose.

DE raises research questions across a wide range of disciplines, and some of these are summarized below:

- The range of scales implied is over at least four orders of magnitude, from a resolution of 10km that would be appropriate for rendering of the entire globe, to the 1m resolution needed to render a local neighborhood. Cartographers have long struggled with relationships between maps at different scales, but not over this large a range.
- Perspectives in DE will be user-centered, whereas almost all cartographic tradition is focused on user-independent perspectives (vertical, with uniform detail). We know very little about how to vary resolution with distance for effective communication, although much work has been done on the necessary algorithms in computer graphics.
- The role of vague information in DE needs to be resolved, as does the importance of providing services that support collaborative work.
- As noted above, DE will have to mix rendering with symbolic and iconic representations. We have little in the way of cartographic technique for indicating the *presence* of information, rather than the content. New forms of representation of metadata are called for.
- The Gore speech implies that a DE environment would somehow know about and have access to some significant portion of the information that exists about a given place. This raises a host of interesting technical questions about information search and discovery in digital libraries, clearinghouses, and the WWW; institutional questions about quality assurance and credibility; and societal questions about privacy and intellectual property.
- Although the child in this scenario enters an immersive, virtual environment, the principles of DE could be applied equally well to the conventional configuration of a user, keyboard, screen, and pointing device. Although the screen renders images in two dimensions, a user with the ability to manipulate rendered objects has no difficulty imagining the object as three-dimensional. But the conventional configuration clearly misses the potential for tactile communication.
- Although the speech refers only to historic data, it is easy to imagine DE being used to communicate simulations of Earth processes that could help the child learn the principles of geomorphology or urban planning and growth; or help decision-makers deal with the

projected impacts of current actions.

- DE will be aided by the development of certain standards, including common ways of representing global geographic data. There are important questions to be resolved about the appropriate organizational frameworks for such standards, since there are many possibilities: the International Standards Organization, the Open GIS Consortium, the Global Spatial Data Infrastructure conference series, or large international software and data vendors.
- DE requires new techniques for overcoming the limitations of bandwidth. These include new methods of compression, and of progressive transmission of various forms of geographic data. Progressive transmission of vector data is an open research issue.
- DE requires a consistent data structure and indexing scheme that can support zoom over 4 orders of magnitude. The scheme that is optimal for display will likely not be optimal for modeling Earth surface processes and compromises will be necessary.
- The mapping needed for DE is not fully available. Although satellite imagery can be composited for large areas of the Earth, topographic information varies widely in scale and availability. Thus DE will require the development of a robust global spatial data infrastructure, and the appropriate organizations to coordinate it.

This list is very partial and preliminary, and it is my hope that the first International Symposium on Digital Earth can extend and clarify it, as the basis for an international effort to begin construction of Digital Earth.

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